THE BASIS OF SCIENTIFIC CHOICE
or
ON CRITERIA FOR PUBLIC SUPPORT OF SCIENCE AND TECHNOLOGY

by

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ABSTRACT

This paper proposes a scheme for rational allocation of public resources for the support of science and technology. The scheme does not aim to supplant decision making by elected or appointed political officials; rather it aims to supplement and rationalize the body of technical information on which their decisions are in part based. The scheme goes out from the explicit recognition that any governmental activity is undertaken for its contribution to a multiplicity of common goals. It then requires any proposed activity to be evaluated with respect to the potential contribution to each of the common goals, as judged by experts with specific responsibility towards that goal. The guiding principle in setting up the evaluation procedures is to seek commensurable alternatives between which choices are to be made. The results of the evaluation process are submitted to the government officials who are responsible for decision, as an input that they are to take into account in arriving at the allocation of government resources. If the scheme proves of any value in its intended application, it can be generalized to aid in establishing priorities among programs within specific scientific-technological missions as well as to aid in allocating government resources among broad national goals.

"We don't seem to receive much help from the scientific community on the question of priorities." Senator Warren G. Magnuson, Chairman, Senate Independent Offices Appropriations Subcommittee, 89th Congress; hearings, 13 June 1966.

I. BACKGROUND

Rationale

This paper presents a scheme for allocation of scarce resources. The larger problem is the allocation of national resources to scientific-technological activity vis-à-vis other activities of the society; the smaller one, the distribution of that portion of national resources devoted to scientific-technological activity among the various disciplines and branches of that activity. We shall limit our concern to what are called the fully developed, industrialized nations, in particular the United States. The allocation in this country is made through a combination of public and private agencies, of which the latter are largely autonomous and currently play the lesser direct role. We shall deal with only the public sector, specifically the preponderant Federal one.

Until recent years[1-5] the mechanisms of allocation did not get much formal attention, primarily because the fraction of public resources devoted to science and technology was insignificant. Now that expenditures on research and development amount to a substantial part of the Federal budget, and indeed several percent of the national product, public scrutiny of the mechanism of allocation is not only fitting but also inescapable.

In the large, we need to demonstrate that the Federal funds allocated to research and development are as effective in contributing to national goals as they would be if they were to be devoted to other areas of public effort - say, education, transportation, recreation - or left in the pocket of the taxpayers to dispose of as they see fit. There can hardly be any argument that in our system of government this kind of allocation must be left up to the Congress acting within constitutional constraints and judicial interpretations. Science and technology, like every other sector of the society, must be allowed to plead its cause, but it can hardly be allowed to judge its case. In the present paper we shall not concern ourselves unduly with the problem in the large, though if the methods to be presented prove to have usefulness, they can be generalized to this wider scope.

In the small, we need a scheme that will lead to equal marginal utility for the expenditures in each discipline and subdiscipline of science and technology. Though it is visionary to expect perfection and universal acceptance of such a scheme, it is defeatist to accept our present hit-or-miss procedures as incapable of improvement. Government officials, legislative as well as executive, are crying out for assistance from the scientific community on the assignment of priorities. The response has largely been silence, broken occasionally by undignified special pleading. We believe that the scientific community owes the Nation and itself a better response. We are not so presumptuous as to offer the present scheme as the answer, but we do hope that it might stimulate development of procedures.

The objection that the scheme gets scientists involved in politics we meet in the standard way - if the scientists don't take care of their own politics, someone else will do it for them only too gladly. In the scheme to be proposed, the scientists get involved in what seems to us to be the least objectionable way: they are allowed and encouraged to present the merits of their case, and they are clearly identified as advocates of their cause. Furthermore, they are allowed and encouraged to assess their own specialty in terms of its potential contribution to the goals of the society. At the least, this experience will enlarge their mind; at the most, it will let their scientific training and competence contribute effectively to attainment of wise decisions. It is not the intent of this paper to develop a scheme that will supplant the political decision-making process by a scientifically-oriented decision-making process executed by scientists: it is rather to propose a scheme that will let the scientists contribute to a better-based procedure for decision making by political officials.

Balance between Freedom from Direction and Support by Public

Let us try to make explicit what is a central point in deciding the proper amount of support that is given science and technology by the public. Sometimes the interplay between the factors to be discussed is described as a conflict. We prefer to describe the interplay as seeking an accommodation rather than besting an adversary. Let us accept the thesis that in the modern world the society cannot thrive without the fruits of science, and that science cannot flourish without the resources of the society. How much freedom should the scientist demand? How much can the society allow? That the limiting cases should be avoided is clear enough. If the performer is completely free from direction by the patron, little support will be forthcoming. If the patron has complete control of the performer, little output will emerge. The internal resources are commanded by the scientist, the external ones by the society. Somehow a balance-point must be established.

Schematically we may represent the situation as in Figure 1. The abscissa is the amount of support given to the scientist by the public authorities, and the ordinate is his freedom from direction by the public authorities. On the xy-plane are plotted curves of constant productivity of the scientific effort ("productivity isoquants"). At present we cannot of course give accepted quantified measures for these variables (except possibly monetary measures for support). Let us first note that the society does not give the scientist complete freedom even with zero public support; certain kinds of investigation are prohibited by convention or by public policy. Hence, a horizontal line is to be drawn at some level below complete freedom, to mark the region above it as a prohibited zone. We note next that even with unlimited public support the number of scientists, not to mention the facilities available to them, is bounded. Hence, a vertical line is drawn to mark a limit beyond which public support is unutilizable. Within the rectangle between the axes and the limit lines, the scientific community and the community at large will establish a working point, corresponding to a certain scientific productivity. It may be possible to change the public support by a certain ammount, at the same time changing the freedom so as to keep the productivity constant. In this way an isoquant of scientific productivity may be traced out. By starting at a point not lying on this isoquant, a new one may be generated. A whole family of such curves thus may be generated, at least conceptually.

To illustrate this idea, consider a community in which a certain level of freedom is acceptable at a given time, though public support of science is zero. Some scientific productivity will still obtain, through private support and as personal hobby, if nothing else. Let us suppose now that the same productivity will result from a modicum of public support, with accompanying prescription of field of activity. Let us suppose further that the greater the support, the greater the restriction, so as to produce a curve decreasing strictly monotonically*.

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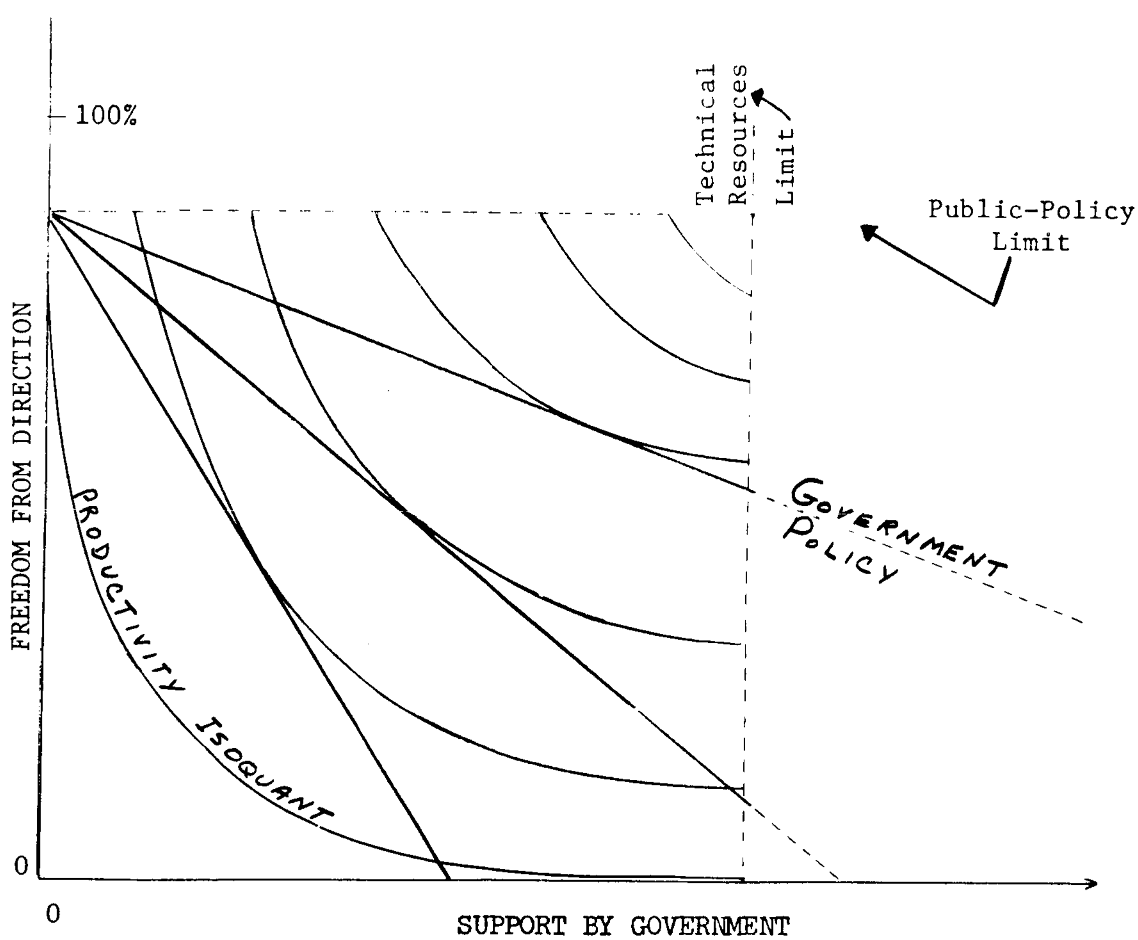
* This assumption is questionable. In its support we have opinions such as those of Michael Polanyi: viz., any attempt at guiding scientific research toward a purpose other than its own is to deflect from the advancement of science. Yet the personal experience of many of us would suggest that though the majority of scientists might thrive under great freedom, some need firm direction. The shape of the aggregate curve would then remain an empirical matter. One might speculate that the personalities and abilities of university investigators lead to the family of curves shown, whereas those of industry investigators lead to the family sloping upward to the right. This description is a way of saying that university research should not be subject to external direction for maximum productivity at given level of support, whereas industry research needs to receive external direction to obtain such pruductivity. To some extent these rules seem to be accepted within developed countries. But it would be difficult to defend the rules rationally, in view of the complexity of the psychological and organizational problems, on which little material and smaller agreement are available.

FIGURE 1


100%
Technical Resources Limit
Public-Policy Limit
GOVERNMENT POLICY
FREEDOM FROM DIRECTION
PRODUCTIVITY ISOQUANT
0
0
SUPPORT BY GOVERNMENT

We can trace out similar curves, beginning with say high amounts of freedom and certain amounts of support depending on the spirit of the community, and watching the curves descend to the left as support grows to sustain activity in prescribed regions.

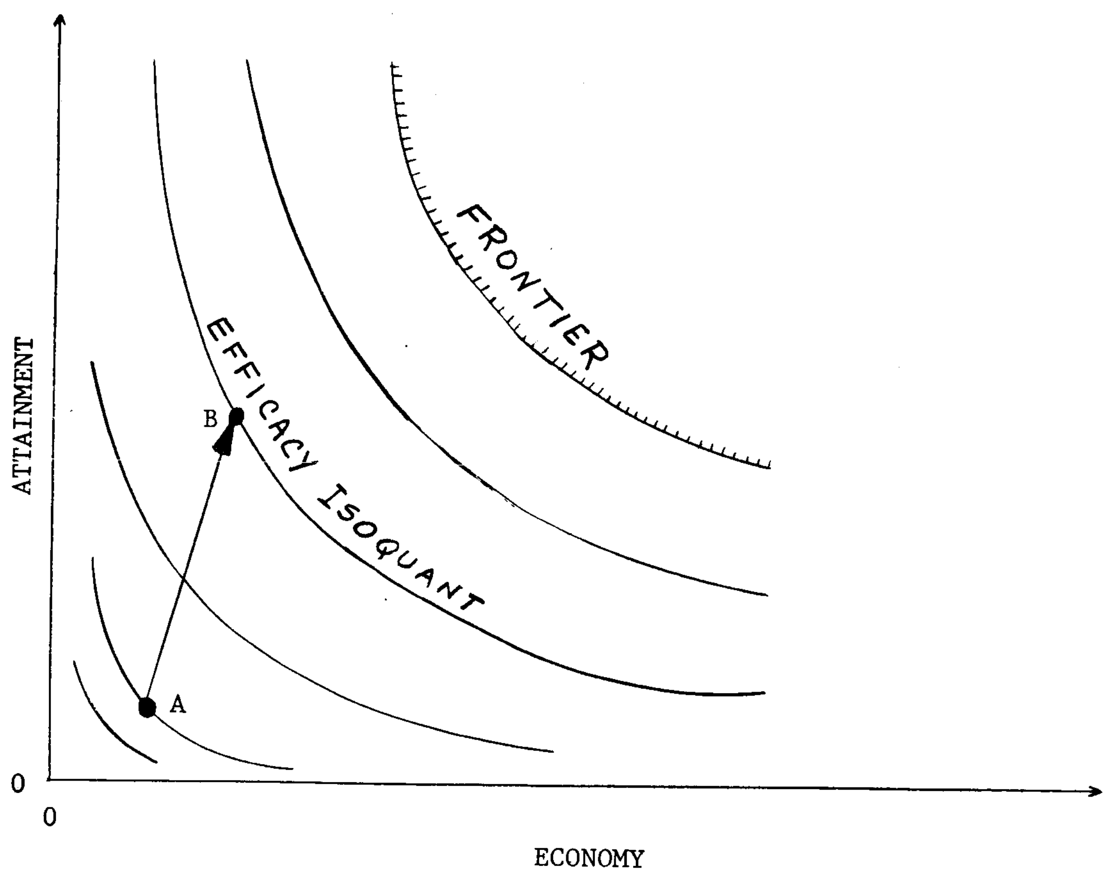
On the same graph we may draw a curve representing the commitment of public resources that the government is willing to make in return for commitment of scientific effort towards specified objectives. For simplicity we have shown this curve as a straight line, though this condition is not essential. The primary reason, of course, for giving public funds to the scientific community for nondirected work is the unpredictability of the applications of science, and we need not expand on this point. From the national standpoint, the optimum operating point will be that of tangency of the public-support line to the appropriate productivity isoquant. This public-support line can be changed of course (as indeed it has, and rapidly indeed during the past twenty years) by influencing public opinion or official practice through education, lobbying, propaganda, and changes in internal and external circumstances. It would take us too far afield to discuss the various factors that can change the slope of the line - we merely cite as examples developments in technology (atomic energy, space vehicles), science (molecular biology), social needs (water supply, atmosphere purification), education (increase of science subjects in curricula), politico-economic developments (level of prosperity, changing military expenditures), and so on. Nor shall we attempt to discuss the factors that determine the social-legal limits placed on the freedom of investigators - they are such as the increasing enlightenment of the community to enable it to accept once-taboo subjects as legitimate matters for investigation (and thereby raise the vertical intercept of the curve), and increasing ethical sensibility on the part of investigators to rule out experiments of potential or actual harm to subjects or third parties, for example, medical experiments on humans, unnecessary cruelty to animals, possible escape of dangerous radioactive materials or of virulent biological materials (and thereby lower the vertical intercept of the curve). These matters are extremely important, but they lie beyond the immediate scope of this paper, though successful resolution of the problem in the small will make some contribution to rational methods for resolving the problem in the large.

Nature of the Scheme

In real-life problems, be they engineering or social, decision making involves a compromise or trade-off among various components of the problems. Yet only narrow aspects of the problems are suited to analytical treatment. True, analytical tools are gradually getting more powerful and sophisticated. Through the centuries and then the decades, arithmetic has been supplemented by algebra, by the integral and differential calculus, the calculus of variations, statistics, computer art and science, linear programming, dynamic programming, and the other appurtenances of operational research and systems analysis. But any practitioner knows how futile it is to try to bring all aspects of the problem under analytical treatment, or even to decide what parts of the organization should be considered within the system under investigation. A "solution" can always be improved in certain aspects, and not necessarily at the cost of other aspects. An <u>optimal solution</u> can be defined as one for which any improvement in one aspect is necessarily at the expense of some other aspect. We wish our solution to attain our long-run objectives completely, but without inordinate consumption of our resources in time or money. The ideal solution would attain our long-run objectives completely, but at infinite cost (zero economy); the completely practical solution entails vanishingly small cost (infinite economy), but makes no progress toward attainment of goals. Schematically, we can illustrate the treatment with the aid of Figure 2. Here the abscissa represents economy in time and money, the ordinate the attainment of long-run objectives. A frontier separates possible from impossible solutions, the optimal solutions lying on this frontier. This curve slopes downward to the right, approaching each axis asymptotically. Solutions less than optimal are represented by points lying between the frontier and the axes. Curves of constant efficacy ("efficacy isoquants") may be located within this region.

Under our present system of scientific choice, we are at some point such as A. Under the scheme proposed herein, we aim to move to some point such as B, at some cost in time and money, but with substantial increase in attainment of long-run objectives. Thus, we move to an isoquant of higher efficacy. We shall surely still be far from the frontier, but we shall have made some improvement. Some other scheme might well be better; if so, let us get on with it. But if we neglect the problem altogether, the increasing complexity of science and technology will likely force the operating point to a curve of even lower efficacy.

FIGURE 2



II. METHODOLOGY OF SCHEME

Basis

The principles on which the proposed scheme is based are the following:

1) Public support of a social activity, specifically of scientific and technological research, is undertaken for the activity's estimated contribution to a manifold of public goals;

2) The organizational structure of the agencies concerned with public support of a social activity is to be so ordered that decisions are to be taken between commensurable alternatives.

Application of these principles can never be wholly satisfactory. With respect to principle 1, the goals are difficult to identify, and the contributions are hard to estimate; with respect to principle 2, alternatives can never be completely commensurable. The principles then can serve only as norms. Even here disagreement occurs. Contrary to principle 1, Michael Polanyi asserts "Any attempt at guiding scientific research toward a purpose other than its own is to deflect it from the advancement of science"; but in a statement that we take to support principle 1, Alvin Weinberg proposes that public support be given to fields according to how they meet three groups of criteria: technological merit, scientific merit, and social merit. Yet, contrary to principle 2, Weinberg believes that "criteria for scientific choice will be most useful only if they can be applied to seemingly incommensurable situations"; but Stephen Toulmin asserts that in most areas of public administration principle 2 is accepted, and that the structures called for have been developed - it is only in scientific matters that the need for such structure has not been recognized and fulfilled.

Discussion of these principles in the abstract is probably idle. The test of them is their utility, and accordingly we propose a scheme exemplifying their concrete application. The scheme, and to a related degree the principles, will stand or fall according to the criteris of feasibility and fruitfulness.

Technique

In qualitative terms, the method consists of the following steps:

1) Categorization of

a) public-welfare sectors (e.g., national security, public health) to which the scientific-technological activity is to contribute; and,

b) scientific-technological activity in terms of technical discipline (e.g., nuclear energy, molecular biology) and in terms of investigator motivation (e.g., basic research, product development).

2) Evaluation of

a) relative contribution of each scientific-technological discipline at each investigator-motivation level to each public-welfare sector. These evaluations are made by experts in each public-welfare sector (e.g., defense officials, public-health officials) following presentations by specialists at each motivational level in each technical discipline (e.g., basic researchers in nuclear physics, molecular biology).

b) relative need for support at each motivational level for each technical discipline. These evaluations are made by managers working in the particular discipline (e.g., industrial-research directors, government-laboratory directors).

c) relative weight of each public-welfare sector by the government officials concerned (e.g., Congressional committees, Bureau of the Budget officials).

d) preliminary warranted allotments that are to be assigned each discipline at each level. These evaluations are primarily a clerical task, and are obtained by combining the relative estimates of 2. a), b), c) to get a single number giving the proportion of the total funds to be allotted to each discipline at each level. This number is then multiplied into the total amount allotted for scientific and technological research and development. The total amount may be one fixed by a public authority, or may be one proposed by an official or unofficial group, depending on the overall purpose and framework of the decisions to be made.

3) Adjustment of preliminary warranted allotments. These allotments are inspected by the public agencies charged with implementing public activities in science and technology. These public agencies may invite private or quasipublic agencies to participate in the inspection. Where serious incongruities appear between the preliminary warranted allotments that the scheme provides, and the funds that the agencies deem warranted, the discrepancies are to be resolved by conference between agencies and estimators, or, that failing, to be reported as alternative estimates. The adjusted warranted allotments (as compromise figures or alternative ones) are presented to the governmental decision-making body for its consideration. It is possible that the evaluation of adjustment steps (and even the categorization!) may have to go through another cycle or two.

Utilization of Results

The decision-making body of course has the authority for making final allocations. In cases where activity has been going on for a more or less extended period (e.g., agricultural research, atomic-power development), the results can be used to estimate how nearly commensurate the activity of a given agency is with its mission. Appropriations for the agency may be reduced or increased, or another agency can be assigned a complementary part of the activity. In cases where a new activity is to be implemented, the results can offer a guide to an appropriate level of funding. The decision-making body naturally will take into account the various political and psychological factors that lie outside the reach of the proposed scheme; but at least that body can recognize explicitly which contributions to its final decision are the consequence of expert informed opinion, and which are imposed by non-technical forces.

We must not expect too much of the scheme. Even if the difficulties to be discussed later could be eliminated, we should still be dealing in an intricate and subtle region of opinion about present matters, not to mention our foretelling the future. Lord Snow[8] has pointed out that "...anywhere, decisions about science and technology have to be taken...No sensible man in any country can afford to be certain that we know the way to take them..." But they do have to be taken, and if the scientific community shirks its responsibility in contributing to the decision-making process, it will lose respect and support by the public and its representatives - and many will say it deserves to. Congress[9], in particular, is showing increasing exasperation with the pleaders for Federal support of science and technology: "...But if the Congress and therefore, the committee, are going to make decisions amongst alternatives, is it not necessary at the time you present alternatives to present some criteria for making the choice and for presenting cost data with these alternatives?..."

III. DETAILS OF TECHNIQUE

Categorization: General Remarks

To a certain extent categorization must be arbitrary. Ideally, we should like to categorize an activity in terms of non-overlapping components referred to bases of comparable magnitude. In mathematical terms, we wish to refer an activity, considered as a vector, to a complete set of orthogonalized and normalized base vectors. The number of base vectors is determined by the nature of the activity and by the purpose of the categorization. Often a given base vector may itself be considered to be spanned by a subset of base vectors; for example, national security may be considered to comprise military, emulation*, and aid components. These components, too, could be broken down further.

Actually finding a complete orthonormal set of base vectors is visionary, and we must be content to seek such a formulation as only a target. As examples of such attempts to categorize public-welfare sectors (PWS), consider Weinberg's proposal of "technological merit," "scientific merit," and "social merit." Here technological merit represents the normal balance between research costs and prospective returns with which the directors of all science-based industries are familiar. Scientific merit is to be measured as much by indirect

* Ordinarily one speaks of "prestige". But "emulation" might be considered a more apt term in that it suggests a motive for achieving prestige. That is, if other nations will accept our way of living because they admire it, we are less likely to have to invoke force to preserve it.

repercussions as by direct promise: "that field has the most scientific merit which contributes most heavily to and illuminates most brightly its neighboring scientific disciplines." Social merit has to do with such things as health, food production, defense, and prestige. We can readily see some shortcomings of this resolution with respect to nonorthogonality (for example, technological merit makes some contribution to social merit) or to completeness (for example, intellectual satisfaction or enlightenment for nonscientists is not explicitly included, nor is economic stimulation). Other resolutions can be suggested, as by governmental function: national defense, international affairs and finances, space research and technology, agriculture and agricultural resources, natural resources, commerce and transportation, housing and community development, health-labor-welfare, education, veterans benefits and services, general government. Or by governmental agency: legislative branch, judiciary branch, executive branch - agriculture; commerce; defense (military and civil); health, education, and welfare; housing and urban development; interior; justice; labor; post office; state; treasury; Atomic Energy Commission; Federal Aviation Agency; General Services Administration; National Aeronautical and Space Administration; Veterans Administration. Or by categories suggested by individuals, for example, Laswell's classification: enlightenment, skills, respect (i.e., status, prestige), affection (i.e., feeling), rectitude (i.e., morality), power, wealth, well-being (health, tranquillity). Each of the classifications mentioned has serious drawbacks, but they illustrate the type of categorization intended. Less accidental classifications might be produced by a group of thoughtful and experienced students drawn from the ranks of universities, industry, government, and foundations. For example, these students might deem the purpose of the government to be providing for the security and the progress of the nation, and might divide the segments into external ones (say military, emulative, supportive) and internal ones (say health, broken down into agricultural, medical, environmental, recreational; economic, broken down into stabilizational and innovational; and so on). This categorization is not ideal, of course; where is "enlightenment" to be included? Does it not make contributions to external segments as well as internal ones?

Similar considerations are relevant for the categorization into scientific-technological disciplines (STD); but here a greater degree of acceptance is probably attainable. Long-established practice has brought about fairly standard categorization, and the subject matter is far less likely to excite emotions. We need decide chiefly what degree of fineness we wish - whether we desire, for example, a very broad division into social sciences and natural sciences; or a less broad division of natural sciences into physical sciences and biological sciences; or a narrower division of physical sciences into mathematics, physics, chemistry, astronomy, geology; or a subdivision of physics into solid-state, molecular, atomic, nuclear, fundamental-particle, and so on. Obviously areas of possible overlap occur (for example, chemical physics and physical chemistry; biophysics and physiology), but through the years separations have been made in practice without encountering insurmountable obstacles.

For the investigator-motivation levels (IML), the arbitrariness of classification is high, but substantial precedent is available to guide us. In this country the classification into basic research, applied research, and development has been pretty well accepted, by both the National Science Foundation[10] and the U.S. Chamber of Commerce[11], to name two established organizations. People have learned to live with the arbitrariness and the overlap of this classification, shifting portions of some activities back and forth as experience dictates. In other lands other classifications have developed. Toulmin in Great Britain, for instance, gives four classes: pure research; speculative technology; product-oriented research; problem-oriented research. In the United States many people would find unnecessary the separation of the final two classes.

At any rate, only experience with the proposed scheme can demonstrate the merits of various categorizations in any of the areas.

Evaluation: General Remarks

Sooner or later, and usually sooner, any attempt to rationalize decision making about human behavior meets head on the problem of value judgments. We have neither the space nor the ability to treat this question. A penetrating, reasoned, and disquieting discussion runs throughout Churchman's Prediction and Optimal Decision[12] (subtitled Philosophical Issues of a Science of Values), culminating in Chapter 7. We fall back on the compelling circumstance that value judgments do have to be made, and we shall not attempt to develop a science of value measurement. But our eyes are not shut to the complexity and subjectivity of the process of judging. As much as feasible, we endeavor to sort out the factors in order to cope with the complexity of the process. And we try to identify and isolate the areas where subjectivity is paramount. We submit, moreover, that the subjectivity is not so high as is traditionally assumed. In the past decade a start has been made on demonstrating that the consensus in human judgment may be quantified. S. S. Stevens[13], basing his statement on earlier work by Thurstone[14] at Chicago in 1929 on attempting to formulate an attitude scale, and on more recent work throughout the world, asserts that "For those who must build their science on one or another consensus of human judgment, a way seems open for an effective quantification." Finnie and Luce at Harvard in 1959, Ekman and his colleagues at Stockholm in 1956 and subsequent years, Indow at Japan in 1959, and others have demonstrated the possibility of obtaining in quantitative terms both reasonable agreement among observers, and simple relations among attitudes quantified by this agreement. Prodigious is the task that remains, yet attainment of quantification with respect to human judgment can no longer be dismissed out of hand.

But because the day of acceptance of quantitative value judgments is not at hand (and also to allow for nonlinearities that are not taken into account in the analytical procedures to be introduced), we attempt to compensate for lack of immediate or even ultimate consensus by introducing an adjustment procedure to give some attention to inconsistencies and disagreements. The adjustment procedure can be made iterative if necessary, but it is unlikely that more than one or two iterations can be justified.

The evaluation procedure consists in having an expert* in a certain field (for instance, public health) estimate the relative potential value of given activities (for instance, atomic energy, molecular biology, astronomy) in contributing to national goals in his field, after specialists in the given activities have had a chance to present their cases before the expert. This evaluation has three successive stages, corresponding to the three categorizations listed earlier. We now formalize this process.

Stage I: Experts in the k-th PWS estimate the relative value $x_{ij,k}$ of the i-th STD at the j-th IML, following briefing of the experts in the k-th PWS by specialists in each of the ℓ STD's at each of the m IML's. It will be convenient to normalize the sum of the estimates for a given STD and a given IML to 100% $\left(\sum_{k=1}^{n} x_{ij,k} = 1 = 100\%\right)$. We thereby generate a <u>crude efficiency matrix</u> $x_{ij,k}$.

* Of a body of experts who have adopted some procedure to attain some kind of consent.

Stage II: For each of the ℓ STD's, managers experienced in that STD estimate the relative claims p_{ij} of each of the m IML's. It will be convenient to normalize the sum of the estimates for a given STD to 100% $\left(\sum_{j=1}^{m} p_{ij} = 1 = 100\%\right)$. Each term of the crude efficiency matrix $x_{ij,k}$ is multiplied by the corresponding p_{ij} to produce a *weighted efficiency matrix* $y_{ij,k}\left(y_{ij,k} \quad p_{ij}\, x_{ij,k}\right)$.

Stage III: For each of the PWS's, the legislators (or their delegated aides) estimate the *relative importance* w_k of each of the m PWS's, following presentations by experts in each PWS if the legislators desire. It will be convenient to normalize the sum of the w_k to 100% $\left(\sum_{k=1}^{m} w_k = 1 = 100\%\right)$. Each term of the weighted efficiency matrix $y_{ij,k}$ is multiplied by the corresponding w_k to produce a *preliminary effectiveness matrix* $z_{ij,k}\left(z_{ij,k} = w_k\, y_{ij,k}\right)$.

Adjustment: General Remarks

The need for adjustment is at least three-fold - first, the value judgments inherently cannot be made exactly or accurately; second, the effectiveness of a particular activity may be so low that funding at the warranted level would be beneath a critical level and thus be ineffective and wasteful; or, on the other hand, so high that supporting it would be beyond the Nation's resources in manpower or material; and third, relative allotments might be politically incongruous and inacceptable. In the second and third cases, the discrepancy between the warranted allotment and the practicable one serves as a warning signal to the Nation.

Ideally, all the persons who have participated in the preliminary evaluating steps should have had a chance to revise their estimates following conferences with other participants. Iteration will lead either to converging estimates, or to irreconcilable differences that would be recognized and reported. It is probable that actual revision according to the process outlined would be required only where novelty is high or special interest is excessive. Most of the time it would be sufficient for the administrators of the agencies who have the responsibility for carrying out the program to inspect the preliminary warranted allotment, and to hold conferences with the evaluators wherever the views of the administrators differ strongly from those of the evaluators. Certainly the administrators are not neutral parties, but their very commitments insure that their missions will not suffer inattention. Moreover, the administrators must have broad views of their programs. If acceptable compromises are achieved, the revised figures can be submitted as adjusted warranted allotments. If such compromises are not achieved in the conferences, the alternative figures are to be presented to the final authority, with as much supporting material as the final authority is willing to consider and the contending parties are willing to submit.*

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* Actually a secular adjustment mechanism is built into a representative form of government. Budgets and performances in successive years give a sensitive indication of imbalances in allocations. This inbuilt mechanism need not be recognized explicitly in our scheme, but it should be kept in the back of the mind as a kind of fundamental corrective feedback process that will keep doctrinaire schemes from going wildly astray. True, this mechanism is not appealing for its logical neatness, but its strength cannot be doubted.

Now we must extend our formalism to handle that part of the adjustment process where the agencies are involved. Since budgets are the natural or at least the standard language for expressing allocations and priorities, we first translate the dimensionless effectiveness matrix into monetary quantities. This translation is made by assuming that the governmental authority is willing to allocate a total sum V to all the STD's at all IML's for all PWS's. To some extent this assumption begs the question, for the total amount V will depend on the success of the agencies or their champions in persuading higher authorities or the public that a higher allotment is needed. Or, from another point of view, the allocation procedure being proposed herein is merely a sub-case of a general allocation procedure, wherein the amount V is allocated from a general total of all government expenditures in terms of its claims in competition with other sectors of the public weal. And even this grand total is subject to modification by the legislature in response to its views and the pressures on it. This modification, too, is in part controlled by the effectiveness of the champions of research and development in pressing their case. In other words, adjustment and feedback are intrinsic parts of the process, at all levels at all times.

In any event, we need to get dollar figures that can be appreciated by agency administrators, executive officials (specifically those in the Bureau of the Budget), and legislative officials (specifically Congressional committees or subcommittees and their staffs).

We transform the preliminary effectiveness matrix $z_{ij,k}$ into a <u>preliminary</u> <u>warranted-allotment</u> <u>matrix</u> $G_{ij,k}$ by multiplying each $z_{ij,k}$ into V, where V is either a prescribed total amount or a projected one, as the circumstances demand:

$$G_{ij,k} \equiv z_{ij,k} V. \qquad (i = 1, \ldots \ell;\ j = 1, \ldots m;\ k = 1, \ldots n)$$

Each element of this ℓ x m x n matrix represents the support warranted for the i-th discipline at the j-th level with respect to its estimated contributions to the k-th sector (for example, support for molecular biology at the basic-research level with respect to the estimated contribution to public health). These matrix elements are not of much appeal to practical-minded administrators (or theoretical-minded ones either).

The two-dimensional matrix G_{ij} obtained by summing $G_{ij,k}$ over k, however, has fairly direct apprehensibility:

$$G_{ij} = \sum_{k=1}^{n} G_{ij,k}. \qquad (i = 1, \ldots \ell;\ j = 1, \ldots m)$$

This element represents the amount warranted for support of the i-th STD at the j-th IML (e.g., for the support of molecular biology at the basic-research level) for all PWS's (i.e., with a view to the contribution of this activity to all sectors of the public weal). We may reduce the ℓ x m x n matrix G_{ij} to a one-dimensional matrix, or vector, by summing over either index. If we sum over j, we get the vector

$$\bar{G}_i \equiv \sum_{j=1}^{m} G_{ij}, \qquad (i = 1, \ldots \ell)$$

each component of which represents the amount warranted for the support of the i-th STD at all IML's (e.g., for the support of molecular biology at all levels for all purposes). If we sum over i, we get the vector

$$\tilde{G}_j \equiv \sum_{i=1}^{\ell} G_{ij} \qquad (j=1,\ldots m)$$

each component of which represents the amount warranted for the support of all STD's at the j-th level (e.g., for the support of all disciplines at the basic-research level for all purposes - in short, for all "basic research").

If now we sum either $\bar{G}_i$ over i, that is, over all disciplines, or $\tilde{G}_j$ over j, that is, over all levels, we get the amount warranted for support of all disciplines at all levels, that is, the quantity

$$V \equiv \sum_{i=1}^{\ell} \bar{G}_i = \sum_{j=1}^{m} \tilde{G}_j = \sum_{i=1}^{\ell} \sum_{j=1}^{m} \sum_{k=1}^{n} G_{ij,k}$$

the total amount warranted for support of research and development activities at all levels over all disciplines for all purposes.

Once the preliminary warranted amounts $\bar{G}_i$, $\tilde{G}_j$, and V have been figured, they should be inspected (insofar as feasible) by the specialists, experts, managers, and legislators to eliminate, reconcile, or identify serious incongruities and disagreements. Such inspection will expedite the formal adjustment process to be carried out with the representatives of existing agencies (and with spokesmen for activities not yet under the aegis of an existing agency, where so indicated).

We may now begin the formal adjustment process. The agency administrators are to inspect the preliminary warranted allotments G_{ij} , and when a severe disagreement exists between the G_{ij} as just determined, and an administrator's estimate of this quantity, the administrator is to confer with the appropriate experts, managers, and legislators (with any party being free to call upon specialists for additional briefing). If the concerned parties can agree on a compromise figure for a given G_{ij} , this single figure is to be entered as the <u>adjusted warranted allotment</u> G'_{ij} ; if they cannot, their separate estimates are to be entered to give a G'_{ij} that has two components.

It may - indeed, it will - happen that some over-riding political or technical considerations require that the total sum be changed.* For example, developments in a field of potential defense applicability (such as in space technology) may necessitate a substantial increase in the total, or changes in the Nation's economy (such as a recession) may require a substantial decrease. Hence, we should permit the preliminary total V to be replaced by an adjusted total V'.

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* The adjustment process might go through additional stages; in that case a (primed) quantity adjusted from its (unprimed) value would be replaced by a double-primed quantity as a result of the second adjustment, by a triple-primed one as a result of the third, and so on. Actually the notation (not to mention the process) would be getting pretty top-heavy by then.

....

In retrospect, we have given to the two sets of special pleaders, <u>viz</u>., the first, the specialists in the disciplines at each level, and the second, the agency administrators charged with furthering their individual missions (or other dedicated persons), a chance to be heard by evaluators that are to a substantial extent impartial with respect to the decisions that they must make. And in the process, we have tried to let the evaluators choose between commensurable alternatives on which they have had the opportunity and responsibility to become informed. Thus, an expert in military applications of science and technology might evaluate the relative potential contributions of molecular biology, nuclear energy, and astronomy to his mission; a manager of a government installation charged with exploiting the field of nuclear energy might evaluate the relative potential contributions of basic research, applied research, and development in this field; a legislator or a legislative committee might estimate the weight to be given arms potential vis-à-vis national prestige or public health and so on. Every faction has a chance to be heard by its judges, and every judge has the chance to become informed.

COMPARISON OF WARRANTED AMOUNTS WITH ASSIGNED AMOUNTS

Now that we have our G'_{ij}, what may be done with them? These are "warranted" amounts in the sense that they represent estimates by competent judges who have had an opportunity to become acquainted with the relevant factors. If a funding allocation has not been made earlier, the G'_{ij} can constitute the basis for it. If a funding allocation has been made earlier, the G'_{ij} can be compared with the amounts that were provided under the previous schedule. For convenience, let us call these amounts "assigned amounts." They may be authorizations, appropriations, obligations, expenditures, or components of any of these, according to how the agencies care, or are forced, to break them down.

To describe this process we introduce a formalism to characterize the agency assignments. Suppose that we have ν agencies, labeled by the superscript $\alpha (\alpha = 1, \ldots \nu)$. Each agency will have a total authorization Γ^{α}, but all that concerns us is the portion of it that is assigned to activity in science and technology. Designate by Γ^{α}_{ij} $(\alpha = 1, \ldots \nu;$ $i = 1, \ldots \ell;$ $j = 1, \ldots m)$ <u>the amount assigned by the α-th agency for research in the i-th STD at the j-th IML</u>. If we sum these amounts for all agencies, that is, over α, we get an $\ell \times m$ matrix

$$\Gamma_{ij} \equiv \sum_{\alpha=1}^{\ell} \Gamma^{\alpha}_{ij} . \quad (i = 1, \ldots \ell; \; j = 1, \ldots m)$$

as <u>agency assignments for all government support of the i-th STD at the j-th IML</u>. It is this quantity which can be compared with the G_{ij} defined previously as

$$G_{ij} \equiv \sum_{k=1}^{n} G_{ij,k} \quad , (i = 1, \ldots \ell; \; j = 1, \ldots m)$$

the preliminary warranted allotments for all government support of the i-th STD at the j-th IML.

Either explicitly or implicitly the total of the agency assignments for science and technology is an important datum. This amount we call W, obtaining it by summing the Γ_{ij} over all i and j:

$$W = \sum_{i=1}^{\ell} \sum_{j=1}^{m} \Gamma_{ij} .$$

For purposes of further analysis, and perhaps for use in the adjustment process, it is advantageous to define, in analogy with $\bar{G}_i$ and $\tilde{G}_j$, the vectors $\bar{\Gamma}_i$ and $\tilde{\Gamma}_j$:

$$\bar{\Gamma}_i \equiv \sum_{j=1}^{m} \Gamma_{ij} , \qquad (i = 1,\ldots \ell)$$

each component of which represents the agency assignments for the support of the i-th STD at all IML's; and

$$\tilde{\Gamma}_j \equiv \sum_{i=1}^{\ell} \Gamma_{ij} , \qquad (j = 1,\ldots m)$$

each component of which represents the agency assignments for the support of all STD's at the j-th IML. It is obvious that

$$W = \sum_{i=1}^{\ell} \bar{\Gamma}_i = \sum_{j=1}^{m} \tilde{\Gamma}_j .$$

The legislative body will surely wish to compare W, the total of the agency assignments for science and technology, with V', the total of the adjusted warranted amounts. The legislative body's initial judgment as to the congruence between W and V', however, is likely to be highly tentative, until it has heard the reaction of the agency administrators to the detailed differences between G_{ij} , the preliminary warranted allotment of the i-th STD at the j-th IML, and Γ_{ij} , the actual agency assignment for that activity. Each agency should have both the opportunity and the responsibility to discuss with the legislative body the commensurateness of its support of each discipline at each level with reference to its mission. It may turn out, on the one hand, that the total of the agency assignments for basic research in astronomy, say, falls far below the total of the warranted allotments. Mission-oriented agencies to which progress in astronomy is highly relevant, such as NASA, Weather Bureau, or Air Force, could then ask for additional funds for supporting such activity; or they could request that the NSF, as an agency charged specifically with support of basic research, make up the difference. On the other hand, it may turn out that a mission-oriented agency is supporting a field to a degree that would seem to exceed the reference terms of its mission. The legislative body - in case it is not convinced or persuaded by the agency's explanation - can then recommend a decrease in support of that activity at that level for that agency, with transfer of a portion of responsibility to another agency if support is justified, or it can reccommend a decrease in total support. Officials in both the legislative and the executive branch will thus have a more solid basis for evaluating the appropriateness of the total effort and its distribution among agencies concerned.

The scheme endeavors, in the language of economics, to furnish the legislative body with the requisite information for transferring resources from one activity to another so as to equalize the marginal productivity of each activity. True, the scheme treats the relations among the variables as linear, which they are surely not. Through the adjustment procedure, nevertheless, this objection can largely be met. In fact, the initial handling of them in the nonlinear case would be by an iterative process not differing too much in consumption of time and effort from the adjustment process suggested.

In practice, naturally, the scheme would be adopted on a continuing basis, with experience from year to year leading to regular adjustment, and to identification and perhaps isolation of intractable regions. But a kind of convergence may be expected, so that the errors in the estimates will produce consequences less serious than those resulting from autonomous disturbances to the allocation process such as breakthroughs in technology, changes in prosperity level, shift in ruling party, and developments in foreign relations.

IV. LIMITATIONS AND CAUTIONS

In the Small

1) Difficulties in the categorization process. The problems arising in this step are first, choosing the agents responsible for the categorization, and second, choosing the basis for the categorization.

With respect to the agents, we need concern ourselves with their impartiality and their competence. It is unlikely that bias is a real danger to jeopardizing the scheme, for the results of the categorization will be open to scrutiny by all the participants in the evaluation process, who collectively have specialized competence in the entire subject matter to be categorized. Severe incongruities would surely be noticed and their consequences discounted. More formidable is the task of finding people of requisite breadth and maturity who can devise acceptable categorizations. It is probably beyond human ability to find completely satisfactory classifications, and only experience will tell us whether sufficiently talented persons become available for the task.

With respect to the basis, we need concern ourselves with its being complete and its being orthogonal. By "complete" we mean that the categories must make room for all the elements of the topic being considered. For example, the categorization of the public welfare into sectors must contain sectors which take into account all aspects of public welfare - thus medical progress, for instance, must either be subsumed under a wider sector (say health) or be listed as a separate sector. By "orthogonal" we mean that each element of the topic being considered must be included in only one of the categories. For example, each aspect of science and technology must be included under only one scientific-technological discipline - thus "biochemistry" must not be subsumed under both "biology" and "chemistry" taken as wider separate categories, and thereby have its potential contribution counted twice.

Even though ideal bases cannot be attained, practical completeness can be obtained by placing overtly omitted elements more or less arbitrarily into some accepted category. Deeper problems appear when the scope of the topic is extended beyond its traditional boundaries, as when the conception of public welfare is gradually widened, or when novel disciplines appear as claimants for admission to the traditional list. Then new elements may be overlooked. Orthogonality, even practical, is not so easily obtained, and we must hope that its lack can be compensated for by means of the adjustment process, which should make clear the region of overlap of categories.

2) Difficulties in the evaluation process. The problems arising in this step occur primarily in selection of the agents responsible for the evaluation. Obviously they should be competent, and we should expect no great difficulty in finding such people. Bias in favor of their own specialties and responsibilities is to be expected. This bias, however, is essentially neutralized by making it largely irrele-

-vant in a specific evaluation. For example, the manager of an atomic-energy national laboratory evaluates relative claims of basic research, applied research, and development only in the field of atomic energy, and hence his legitimate bias towards atomic energy cannot influence the claim of atomic energy versus molecular biology or space science. An individual evaluator may, of course, be biased with respect to subjects that he is evaluating, though he has no professional commitment to any of them; but this bias, if ever suspected, can be taken into account by comparing his evaluating with that of several of his peers. For example, a military-defense expert may judge that high-energy physics is of greater potential benefit to the mission of his agency than is molecular biology; if there is any reason to suspect the impartiality of this judgment, other military-defense experts can be consulted, and their opinions taken into account in assessing the soundness of the judgment of the first expert. Such a procedure does not guarantee either fairness or correctness, but it discourages flagrant distortion attributable to bias.

With respect to the basis for estimating the potential contributions or importance of a given topic, we admit at the outset that value judgments are subjective. We are sanguine, nevertheless, about the prospect for achieving reasonable agreement on effective quantification of values on existing situations, as we have set forth in Section I. On situations of the future, we are not so hopeful.

Estimating the potential contribution of high-energy physics to medicine, for example, means multiplying an unforeseeable gain by an unknowable probability. The traditional example of Roentgen's work in atomic physics with gas-discharge tubes, which led to the discovery of X-rays, shows how hard it is to figure odds in the scientific lottery when the payoff is in social gain.* It is our feeling that this part of the problem may well be incapable of resolution, and will retreat into the dark realms of the psychology of betting. But its very consideration should neutralize the arm wavers, and force the discussion into a more sensible basis.

3) Difficulties in the adjustment process. Here at least we are in no quandary about agents, for as evaluators they have already been selected earlier. Detailed procedures are a little vague to foresee, and it is probably premature to make too specific recommendations. The adjustment is a kind of bargaining process, for which a large body of practice and a small literature of theory exist. Most closely related experience would seem to be exemplified in Senate-House committee conferences, and business or university budgeting sessions. Direct antagonism, as is characteristic of say labor-management disputes, seems foreign to the kind of meeting-of-minds that is indicated.

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* To make matters worse, even when the probabilities and the payoffs are known, humans often operate with a subjective probability different from the objective one, particularly when it is very low.

4) <u>Complexity and unwieldiness</u>. The scheme is obviously complex, but so is the subject matter with which it deals. The complexity entails two disadvantages. The first is readily apparent, that it engenders expense in time and money; the second is less perspicuous, that complexity of the special kind involved here tends to repel legislators, however cozily it may nestle down in the intricacy-loving mind of academics. As a consequence the scheme will meet an unsympathetic reception above and beyond what it deserves on the basis of its intrinsic demerit. The technical staff of a legislative committee, however, may not be repelled by the complexity, and can interpret the conclusions to the committee and render the scheme palatable.

Unwieldiness is a relative matter, and cannot be judged apart from comparison with alternatives. Dedication and ingenuity, moreover, can do much to mitigate the weightiness. Only experience will tell.

<u>In the Large</u>

1) <u>Difficulties arising from incompleteness</u>. The scheme does not take explicit account of the private sector in supporting science and technology. In the adjustment process, however, some accomodation may be made. For example, a field of borderline acceptability or of marginal promise tends to be rejected out of hand for public support if private funds are available. In a way such action is regrettable

though probably inevitable. Less fashionable fields thus tend to get shortchanged, as in any system where sins of commission are obvious and sins of omission are not.

2) Difficulties arising from unacceptability. Some persons will find the scheme unacceptable in principle because it appears to lend the trappings of scientific procedure to what is in its essence a non-scientific process. Yet even if we can give meaningful definition to "scientific" and "nonscientific" in the present context, we can say that what the scheme tries to do is to make very clear which aspects of the problem are amenable to scientific procedures and which aspects are not. Like any other tool, the scheme can be used or abused. Other persons will find the scheme unacceptable because of impracticality; only experience can show to what extent it may be useful.

3) Difficulties arising from success of the scheme. If the scheme were to prove highly successful, two dangers are to be anticipated. The first is that the scheme might tend to encourage unimaginativeness because it favors fashionability and quantifiability in fields receiving support. Perhaps the best safeguard would be to have only very general allocations made at high levels, with detailed funding left autonomous at the lowest levels possible. The second danger is a related one: the scheme might render government support too monolithic, with the consequence that an unpopular field might

be shut out from all support. So long as cocksureness concerning the ability to foresee the future exceeds success in foreseeing it, alternative routes for implementing unfashionable fields need to be accessible.

V. POTENTIAL BENEFITS

Educative

1) To members of the scientific-technological community. Enough utterances from the spokesmen for science and technology are on record to demonstrate the insularity with which many of its practitioners view the role of the government in giving support to their occupation. Among the more widely-circulated fatuities are the extravagant or trivial claims made for high-energy physics, Mohole, and space science on the one hand, and the intemperate and illogical criticism of these same activities on the other. Anyone who follows through the scheme's procedures for identifying the elements of scientific choice that are amenable to rational approach, and for listing the components of the public weal to which any government-supported activity is supposed to contribute, cannot help gaining an appreciation of how the rest of society will look at his activity, and of the degree to which his position has only emotional rather than logical strength. Thus education of the elite will proceed.

2) To nonmembers of the scientific-technological community. Anyone who cares to follow the procedures in the scheme will gain an idea not merely of the material benefits resulting from science and technology (which topic has been labored beyond endurance), but also of the intellectual and humanistic fruits of such activity. For instance, one may gain an appreciation of the intellectual satisfaction and stimulation, and of the emancipation from irrational fears, that attend the enlightenment that science throws on natural processes.

Indicative

The scheme will identify disciplines in science and technology that may be receiving support out of proportion to their estimated contribution. The disproportion may be in either direction, of course. The scheme should be viewed as merely an identifier of fields that bear examination, rather than as a positive indicator of out-of-balance. Its value here may be important without being harmful - fields that stand suspected of obtaining support greater than warranted will have their champions in any event, who may indeed be vindicated; whereas the fields that are promising but not prominent will have attention drawn to them and hence will require positive action in order to be slighted, in contrast with the present situation where they require positive action to avoid being slighted.

Efficiency-producing

The scheme in essence produces a kind of "equal marginal utility" for the support of each discipline, as measured by the categorization-evaluation-adjustment process. We may hope that the persons involved in the process are reasonably competent and well-informed, and we have tried to build into the scheme some provisions to utilize their skills and minimize the consequences of their biases. It is important to bear in mind that the scheme is not intended to allocate the resources. The scheme is intended to inform the decision makers concerning allocations that produce efficiency as judged by the interested parties, and to let the decision makers (and the public to whom they are responsible) see clearly, and thereby be in position to defend effectively, any depar-

-tures from efficiency that they make for external reasons, as for instance acceptability to the public, response to pressure groups, political trade-offs, economic disequilibrium, and so on.

Benefits resulting from unwieldiness

1) From complexity. The complexity of the scheme renders it difficult for unscrupulous participants to calculate accurately the effects of any machinations. Attempts at disingenuousness may well be detected somewhere during the adjustment process, and even if they are not, they may well produce effects opposite to those intended. Thus, overselling a discipline may produce an excessively high rating for it, but may lead to incongruities in totals or in agency assignments: the net advantage may be zero or negative.

2) From difficulty. The difficulty of completely satisfactory categorization and the difficulty of acceptable evaluation will keep the scheme from being taken excessively seriously. Hence, pleaders within a given discipline or within a given agency will be able to maintain that some channels must be available outside the scheme. We agree whole-heartedly; but at the same time we have deliberately placed the burden of proof upon the pleaders. At any rate, the difficulties inherent in the scheme would seem to provide a safeguard against its creating a monolithic structure for government support of science and technology.

VI. GENERALIZATIONS AND REFINEMENTS

Generalizations are obviously to be considered in extending the principle of the scheme downward to subdivisions in each class, for example, assigning priorities to missions within a program; or upwards to categories of wider scope, for example, allocating resources among department and independent offices of the Federal government.

Refinements are possible in generating more sophisticated and complete categorizations, in particular in attempting to find different bases for the public-welfare sectors, and in calculating the adjusted warranted allotments to them. Insofar as the two different bases are complete and orthogonal, they should give the same adjusted warranted allotments. If they do not, the discrepancies will at least give clues about where the formulations are inadequate.

Extensions are possible in getting evaluations from wider classes of participants. In particular, it might be possible to include the specialist in the scientific-technical disciplines in the judging process. These specialists could be briefed by the experts in the public-welfare sectors, and perhaps receive general guidance from the decision-making body before making their estimates. They could produce their preliminary warranted allotment matrix, which could be compared with that produced in the present scheme. It might be possible to combine both sets of estimates to produce a single averaged matrix. Whether the symmetry added by such a procedure would make the process better or worse is a question that bears study.

Parts of the scheme could be utilized by bodies other than the decision-making one. For example, the Bureau of the Budget, an arm of the executive branch, might find the matrix useful in preparing the budget for submission to the legislative branch; or a private foundation might be willing to provide support to areas suggested by the scheme, but which for one reason or another cannot receive adequate governmental support.

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REFERENCES

1. Edward Shils, Minerva I (Autumn, 1962), 1, p. 5, Editorial Manifesto.

2. Michael Polanyi, Minerva I (Autumn, 1962), 1, pp. 54-73, "The Republic of Science: Its Political and Economic Theory."

3. Alvin M. Weinberg, Minerva I (Winter, 1963), 2, pp. 159-171, "Criteria for Scientific Choice"; Minerva III (Autumn, 1964) 1, "Criteria for Scientific Choice II: The Two Cultures."

4. C.F. Carter, Minerva I (Winter, 1963), 2, pp. 172-181, "The Distribution of Scientific Effort."

5. John Maddox, Minerva II (Winter, 1964), 2, pp. 141-159, "Choice and the Scientific Community."

6. Stephen Toulmin, Minerva II (Spring, 1964), 3, pp. 343-359, "The Complexity of Scientific Choice: A Stocktaking."

7. Bruce L.R. Smith, Rand Report P-3156, June, 1965, "The Concept of Scientific Choice: A Brief Review of the Literature", an abridged and somewhat updated version appears in The American Behavioral Scientist, May, 1966.

8. C.P. Snow, Science 151, 650 (11 February 1966).

9. Hearings before the Committee on Aeronautics and Space Science, U.S. Senate, 89th Congress, 2nd session on S. 2909, 28 February - 4 March 1966.

10. National Science Foundation, NSF-65-13, p. 4, Surveys of Science Resources Series.

11. Committee on Science and Technology, Chamber of Commerce of the U.S., "Criteria for Federal Support of Research and Development," 1965.

12. C. West Churchman, "Prediction and Optimal Decision," Prentice-Hall, 1961.

13. S.S. Stevens, Science 151, pp. 530-541 (4 February 1966).

14. L.L. Thurstone, University of Chicago Press, Chicago I.U. (1929).